UNDERLINE PHYSICS OF E-MEVVA OPERATION:
Explaining Past Results, Guiding Future Improvements

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Recently substantial enhancement of high ion charge states was clearly observed in both the HCEI and ITEP E-MEVVA ion sources. These experimental set-ups have two different methods of measuring the ion charge state distributions. The results can be considered as a proof of the E-MEVVA principle. These results sparked discussions regarding, which physics effects are dominant. Basic physics seems straightforward, an ion charge state in E-MEVVA is determined by the number of collisions with fast electrons versus the number of encounters with neutrals and lower charge state ions during an ion dwell time in the drift channel. However, the fluxes of fast electrons, lower charge state ions, and neutrals encountered by an ion may be a consequence of numerous effects. Factors determining neutral fluxes might be poor vacuum conditions, desorption of adsorbed gas by the electron beam directly or indirectly due to stacking (E-beam reflection) and/or instabilities that cause heating and desorption. Flux and energy of the fast electrons is primarily determined by the electron gun output. But significant contributions from electron beam stacking, instabilities, as well as plasma electron heating, are possible. The various contributions are evaluated to account for past results and to guide future progress.

1. Introduction

Metal Vapor Vacuum Arc (MEVVA) ion sources [1] are used to generate high current pulsed ion beams for both fundamental [2] and applied [3] research. The MEVVA is a prolific generator of highly ionized metal plasma from which metallic ions are extracted. A generic MEVVA [1] consists of a series of electrodes (usually concentric) that are separated by ceramic insulators. The commonly used configuration is a solid electrode of the desired metal, followed by a trigger electrode, an anode, a suppressor, and a three-grid extractor. Triggering of the vacuum arc is accomplished by applying a short high voltage pulse between the trigger electrode and the cathode across an insulating surface. Vacuum arc discharge occurs due to formation of cathode spots, which are micron-sized spots on the cathode surface characterized by extremely high current densities. Small spots on the cathode material are vaporized and ionized, producing a plasma plume, from which ions are extracted. Although a MEVVA plasma is characterized by a high degree of ionization, only low ion charge states are typically extracted. Depending on the cathode material used a conventional MEVVA ion beam has a mean charge state Q of about 2+.

For many applications [2,3] it is highly desirable to enhance the MEVVA ion charge state so that the ion beam energy can be increased without applying higher extraction voltage. Previous efforts demonstrated that the mean ion charge state in vacuum arc plasmas could be increased in a strong magnetic field [4,5], with high arc current [5], or by applying an additional short current "spike" on top of the main arc current [6]. Most previous attempts to obtain higher charge states quickly reached saturation [7] at charge states only 1.5 to 2 times higher than the conventional MEVVA. However, one promising approach is to attempt ion charge state enhancement using an energetic electron beam. Sources like the Electron-Cyclotron Resonance (ECR) and Electron-Beam Ion Source (EBIS) also use energetic electrons to produce high ion charge states, but the ion beam currents are typically orders of magnitude lower than MEVVA. Hence, the purpose of E-MEVVA is to obtain both large ion currents and high charge states.

Over 30 years ago Donets invented the EBIS [8], in which a high-energy, high-density electron beam produced multiple ionization of gaseous ions. Later, Batalin, et al. [9] combined an electron beam, a vacuum arc ion source, and a drift tube into a source called E-MEVVA, which produced encouraging indications of higher charge state production. Then, Hershcovitch, et al. [10] extended this concept using a Z-discharge plasma to generate an internal electron beam. With a gold cathode this Z-MEVVA gave results with some indication [10] of charge states as high as Au^{6+}.

Recently, significant charge state enhancement was report [11,12] in detailed E-MEVVA investigations, which were performed jointly among the Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia, the High Current Electronics Institute (HCEI), Tomsk, Russia, and Brookhaven National Laboratory (BNL), USA. The experiments were performed in Moscow and Tomsk with nearly the same design of ion sources. Substantially higher ion charge states were observed clearly in both experimental set-ups with two different methods of measuring the ion charge state distributions.

In this paper the underline E-MEVVA physics is reviewed. Old results are interpreted, future improvements are proposed.

2. Physics of Charge-State Enhancement and Reduction

When electron-impact dominates ionization like in E-MEVVA, three ingredients are needed: (1) high $J\tau$, which is the product of electron current density J and electron-ion interaction time τ, and (2) high E, which is the effective electron "beam" energy. Donets [13] is credited with illustrating that the maximum charge state achievable for any element can be predicted on a plot of $j\tau$ versus E. Additionally, (3) prevention of charge reduction, which is dominated by exchange with lower charge state ions and neutrals.

When stepwise ionization, by electrons with density n_e and velocity v_e, is the dominant stripping process, the equation describing the rate of change in the number N_q of ions in a charge state q is

$$dN_q/dt = -N_q\, n_e\, \sigma_{q\rightarrow q+1}\, v_e + N_{q-1}\, n_e\, \sigma_{q-1\rightarrow q} v_e \qquad (1)$$

where σ is the cross section for ionization of ground-state ions. A reasonably good expression for σ is Lötz's semi-empirical ionization formula [14],

$$\sigma_{q\rightarrow q+1} = 4.5x10^{14} \Sigma \, (n_j/EI_j) \ln(E/I_j) \qquad (cm^2) \qquad (2)$$

where n_j is the number of electrons in subshell j, I_j is the ionization energy of subshell j in eV and E is the electron incident energy in eV. In the absence of any other processes Eq. 1 can be integrated to yield an expression describing the time evolution of the number N_q of ions in a charge state q as a function of Jτ. The "Donets plot" [13] is obtained by plotting the minimal E required to reach a charge state versus the Jτ, Unlike in EBIS, charge exchange is a very important contributor in plasma heavy-ion sources like the MEVVA and E-MEVVA, because the high charge-state ions interact with newly formed plasma ions and background atoms. To include the effect of charge exchange requires adding to Eq. 1 an additional term

$$dN_q/dt = -N_q \, n_e \, \sigma_{q\rightarrow q+1} \, v_e + N_{q-1} \, n_e \, \sigma_{q-1\rightarrow q} v_e - \Sigma \, N_q \, n_i \, \sigma_{cq\rightarrow q-1} \, v_i \qquad (3)$$

where, $\sigma_{cq\rightarrow q-1}$ is the single electron-capture cross section by charge exchange with ions in the discharge with charge state less than q. These ions have a variety of charge states, n_i and v_i are density and relative velocity (to ions with charge q) in charge state i<q. For $\sigma_{cq\rightarrow q-1}$ there is a simple semi-empirical formula that describes the dependence of this cross section on q and on v_i [15]

$$\sigma(q,v_i) \propto q^a/v_i^m \qquad (4)$$

where the parameters a and m are to be determined from either experimental or theoretical work. In studies with MeV projectiles [15], the value of a was estimated and measured in the range of 2-3.7, while m was 3-4. Our interest is in a much lower (keV) energy range where the value of a may be even larger than 3.7 [16]. Multi-electron capture is rather significant for highly-charged ions, as observed in Kr^{+18} - Ar collisions [17]. A more realistic version of Eq. 4 would require inclusion of multi-electron capture; however only limited data is available. Nevertheless, Eqs. 2-4 indicate that in sources with continuous plasma formation very high charge states cannot be attained in large quantities. The stripping cross section decreases with increase in ionization energy (i.e., charge state), while the electron-capture cross section increases with charge state. Plasma formation rates in heavy ion sources (in which plasma is continuously formed) are usually large enough to result in a significant density of low charge state ions, which in turn suppress generation of high charge state ions. In vacuum arcs with currents of a few hundred Amperes, e.g., typical cathode erosion rate is about 30 μg/Coulomb[18] resulting in an ion current that is roughly 10% of the total arc current [19].

Equations 1 and 3 are based on stepwise ionization of ground state ions. However, charge state formation rates higher by a factor of 2.5 have been observed in Z-pinches [20]. A number of additional contributions may lead to the higher rates, e.g., ionization of excited ions with a cross section larger than Eq. 2; and, excitation - autoionization (Auger) processes. In most plasma heavy ion sources like the EBIS, ECR, PIG, and MEVVA, excited ions decay before collisions leading to ionizations occur. At higher charge states in a typical EBIS, the time interval between successive ionizations is at least a number of milli-seconds, i.e., orders of magnitude longer than the decay time of most excited ions, whereas the whole ionization process in an E-MEVVA lasts for microseconds. The same arguments can be extended to with an intense electron beam. Therefore, Eq. 3 must be modified for such intense devices to include autoionization, ionization of excited ions. Including those contributions yields,

$$dN_q/dt = \Sigma^* \left(-n_q\, n_e\, \varsigma_{q\to q+1}\, v_e + \mathbf{n}_{q-1}\, n_e\, \varsigma_{q-1\to q}\, v_e\right) - N_q\, n_i\, \sigma_{iq\to q+1}\, v \qquad (5)$$

where Σ^*refers to summation over all ion states (ground and excited) $\mathbf{n}_q$ is the density of each state; the total ionization cross section by electron impact $\varsigma = \sigma^* + \sigma^{s+a}$ in which, σ^* in the ionization cross section of excited ion (for which there is no analytical expression and very little data) and σ^{s+a} is the total impact ionization of ground state ions by electron stripping as well as autoionization [a semi-empirical formula for σ^{s+a} can be found in [21]. These terms account for ionization by background ions. A procedure for computing σ_i can be found in [22].

3. Discussion

Equation 3 and the ensuing discussing clearly indicates that, in discharges with continuous formation of neutrals and low charge state ions, very high charge state heavy ions can not be attained in significant quantities. To illustrate this charge-exchange limitation consider the charge changing cross sections [15] of iodine ions passing through a hydrogen target, which for 5 MeV I^{+7} are: 18.5 Å^2 for electron capture (i.e., charge exchange resulting in I^{+6}), and 0.045 Å^2 for electron loss (i.e., ionization resulting in I^{+8}) respectively. As predicted by equations 3 and 4, the data shows that the ratio (of over 400) between these processes (cross sections) is rather unfavorable for high charge state formation. Since the I^{+7} energy is much larger than the hydrogen binding energy, the electron loss cross section is equivalent to ionization by free electrons with an equal relative velocity (as would be the case in an ion source). However, in any conceivable (useful) ion source, the ion energy spread would not exceed a few KeV. Hence, based on equation 5, the electron capture cross section in an ion source would be much higher than that measured in [15]. Furthermore, the data and Eq. 3 indicate a worsening of cross section (charge-exchange/ ionization) ratios with increase in charge state, e.g., the ratio which is (3.54 Å^2)/(3 Å^2) = 1.18 for I^{+2} grows to 411 for I^{+7}.

A simple model [23,24] assumes that the ion charge state distribution in an E-MEVVA (and in some other ion sources), is determined by the balance of electron stripping rate versus neutralization by charge exchange with neutrals and lower charge state ions. The relative fraction of higher charge state ions can be enhanced by raising the intensity of the electron beam in the drift region, and by preventing "fresh plasma" formation during stripping, thus reducing the undesirable effects of charge exchange. To enhance E-MEVVA ion charge states the electron beam currents in the drift tube were raised [11,12] from 1 A to 40 A. To curtail charge state reduction by charge exchange the vacuum systems were improved and the E-MEVVA electron beam pulse was made longer than the MEVVA pulse. If no fresh plasma is generated during most of the electron beam pulse, the unfavorable charge exchange is greatly reduced. Electron stripping to higher charge states becomes the dominant process.

The basic motivations for the improvements above are clear and difficult to dispute; however, implementing these changes resulted in ion charge state distributions that either failed to show any charge state enhancement or showed a mild reduction in high charge state fractions. The culprit was gas generation by the electron beam, which compounded the problem of gas generation by the MEVVA arc. When the electron beam is fired, the impurity ion population increases dramatically due to electrons striking the drift tube walls. The breakthrough [11] came when the MEVVA arc was lowered and the electron beam pulse length was shortened to reduce gas generation.

Surprisingly, the recent E-MEVVA results [11,12] are consistent with $J\tau$ predictions. That is, successive single (stepwise) ionization accounts for the observations. Given the relatively poor vacuum condition during the electron beam pulse, unfavorable charge exchange conditions are likely. The apparent agreement with "$J\tau$ scaling" is most likely the result of multiple ionizations compensating for destructive charge exchange. For high charge states multiple ionization by single-electron impact is greatly reduced. Therefore, reducing gas and impurity ion density is imperative. $J\tau$ must be increased to attain higher charge states.

Strong evidence also exists for electron beam stacking, which has the convoluted contributions of enhancing $J\tau$, while sputtering impurity off the walls. It leads to instabilities, which heat the plasma and increase impurity concentrations. The results are also consistent with an alternative interpretation by A. Andres [25], who suggests that a small increase in plasma electron temperature (resulting from electron beam heating) can significantly increase the population of energetic electrons, and hence, ion charge states.

4. Conclusion

Although E-MEVVA has clearly shown to produce substantially higher charge-state ions than a conventional MEVVA, it may be possible to further optimize the source and to extract even higher charge state ions after the electron beam pulse. Possibilities for future enhancement include (a) increasing the electron beam current and density, and (b) further reducing the negative effect of residual gas impurities. Increasing the electron beam current and density is a straightforward concept. However, the electron gun would have to be completely gasless, unlike the present E-MEVVA electron guns. To prevent formation of impurities, the electron beam, after passing through the drift tube, would be guided into an external beam dump. The beam dump must face away from the ion beam axis to prevent gaseous impurities from streaming into regions where they can interact with the ions. To generate very high charge states, a merging beam approach would be needed.

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